Use the information located at:

<http://science.howstuffworks.com/environmental/energy/solar-cell.htm>

to answer the following questions.

**Introduction to How Solar Cells Work**

The hope for a **"(1)\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_"** has been floating around for decades -- the idea that one day we'll all use free electricity fro­m the [sun](http://science.howstuffworks.com/sun.htm). This is a seductive promise, because on a bright, sunny day, the sun's rays give off approximately **(2)\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_** watts of energy per square meter of the planet's surface. If we could collect all of that energy, we could easily power our homes and offices for **(3)\_\_\_\_\_\_\_\_\_\_\_\_\_\_.**

**What is the purpose of the article? (4)**

**Photovoltaic Cells: Converting Photons to Electrons**

The solar cells that you see on calculators and satellites are also called **(5)\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_** (PV) cells, which as the name implies (photo meaning "light" and voltaic meaning "electricity"), convert sunlight directly into electricity.

A **(6)\_\_\_\_\_\_\_\_\_\_\_\_\_\_** is a group of **(7)\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_**connected electrically and packaged into a frame (more commonly known as a (**8) \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_),** which

can then be grouped into larger solar **(9)\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_,** like the one operating at Nellis Air Force Base in Nevada.

Photovoltaic cells are made of special materials called **(10)\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_** such as

**(11)\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_,** which is currently used most commonly. Basically, when

**(12)\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_** strikes the cell, a certain portion of it is absorbed within the semiconductor material. This means that the energy of the absorbed light is transferred to the semiconductor. The energy knocks **(13)\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_** loose, allowing them to flow freely. PV cells also all have one or more electric field that acts to force electrons freed by light absorption to flow in a certain direction. This flow of electrons is a current, and by placing metal contacts on the top and bottom of the PV cell, we can draw that current off for external use, say, to power a calculator. This current, together with the cell's voltage (which is a result of its built-in electric field or fields), defines the power (or wattage) that the solar cell can produce.

# How Silicon Makes a Solar Cell

Silicon has some special chemical properties, especially in its crystalline form. An **(14)\_\_\_\_\_\_\_\_\_\_\_\_\_\_**of sili­con has 14 electrons, arranged in three different **(15)\_\_\_\_\_\_\_\_\_\_\_.** The first two shells -- which hold **(16)\_\_\_\_\_\_\_\_\_\_\_\_** and eight electrons respectively -- are completely full. The outer shell, however, is only

**(17)\_\_\_\_\_\_\_\_\_\_\_** full with just four electrons. A silicon atom will always look for ways to fill up its last shell, and to do this, it will share electrons with four nearby atoms. It's like each atom holds hands with its neighbors, except that in this case, each atom has four hands joined to four neighbors.

That's what forms the **(18)\_\_\_\_\_\_\_\_\_\_\_\_\_\_ structure**, and that structure turns out to be important to this type of PV cell. The only problem is that pure crystalline silicon is a **(19)\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_** conductor of electricity because none of its electrons are free to **(20)\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_** about, unlike the electrons in more optimum conductors like copper. To address this issue, the silicon in a solar cell has **impurities** -- other atoms purposefully mixed in with the silicon atoms -- which changes the way things work a bit. We usually think of impurities as something undesirable, but in this case, our cell wouldn't work without them. Consider silicon with an atom of **(21)\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_** here and there, maybe one for every million silicon atoms. Phosphorous has **(22)\_\_\_\_\_\_\_\_\_\_\_** electrons in its outer shell, not four. It still bonds with its silicon neighbor atoms, but in a sense, the phosphorous has one electron that doesn't have anyone to hold hands with. It doesn't form part of a bond, but there is a positive proton in the phosphorous nucleus holding it in place. When [energy](http://auto.howstuffworks.com/auto-parts/towing/towing-capacity/information/fpte.htm) is added to pure silicon, in the form of **(23)\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_**for example, it can cause a few electrons to break free of their bonds and leave their atoms. A **(24)\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_** is left behind in each case. These electrons, called **free carriers**, then wander randomly around the crystalline lattice looking for another hole to fall into and carrying an electrical current. However, there are so few of them in pure silicon, that they aren't very useful.

But our impure silicon with phosphorous atoms mixed in is a different story. It takes a lot less energy to knock loose one of our "extra" phosphorous electrons because they aren't tied up in a bond with any neighboring atoms. As a result, most of these electrons do break free, and we have a lot more free carriers than we would have in pure silicon. The process of adding impurities on purpose is called **(25)\_\_\_\_\_\_\_\_\_\_\_\_**, and when doped with phosphorous, the resulting silicon is called **(26)\_\_\_\_\_\_\_\_\_\_\_\_** ("n" for negative) because of the prevalence of free electrons. N-type doped silicon is a much better conductor than pure silicon.

The other part of a typical solar cell is doped with the element **(27)\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_,** which has only three electrons in its outer shell instead of four, to become P-type silicon. Instead of having free electrons, **(28)\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_** ("p" for positive) has free openings and carries the opposite (positive) charge.

# Anatomy of a Solar Cell

B­efore now, our two separate pieces of silicon were **(29)\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_** neutral; the interesting part begins when you put them together. That's because without an

**(30)\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ field**, the cell wouldn't work; the field forms when the N-type and P-type silicon come into contact. Suddenly, the free electrons on the N side see all the

openings on the P side, and there's a mad rush to **(31)\_\_\_\_\_\_\_\_\_\_\_** them. Do all the free electrons fill all the free holes? No. If they did, then the whole arrangement wouldn't be

very useful. However, right at the **(32)\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_**, they do mix and form something of a barrier, making it harder and harder for electrons on the N side to cross

over to the P side. Eventually, **(33)\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_**is reached, and we have an electric field separating the two sides.

This electric field acts as a **diode**, allowing (and even pushing) **(34)\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_** to flow from the P side to the N side, but not the other way around. It's like a hill -- electrons can easily go down the hill (to the N side), but can't climb it (to the P side).

When light, in the form of **(35)\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_,** hits our solar cell, its energy breaks apart electron-hole pairs. Each photon with enough energy will normally free exactly one electron, resulting in a free hole as well. If this happens close enough to the electric field, or if free electron and free hole happen to wander into its range of influence, the field will send the electron to the N side and the hole to the P side. This causes further disruption of electrical neutrality, and if we provide an external current path, electrons will flow through the path to the P side to unite with holes that the electric

field sent there, doing work for us alo­ng the way. The electron flow provides the **(36)\_\_\_\_\_\_\_\_\_\_\_\_\_\_**, and the cell's electric field causes a **(37)\_\_\_\_\_\_\_\_**. With both current and voltage, we have **(38)\_\_\_\_\_\_**, which is the product of the two.

There are a few more components left before we can really use our cell. Silicon happens to be a very shiny material, which can send photons bouncing away before they've done their job, so an **(39)\_\_\_\_\_\_\_\_\_\_\_\_\_ coating** is applied to reduce those losses. The final step is to install something that will protect the cell from the elements -- often a **(40)\_\_\_\_ cover plate**. PV modules are generally made by connecting several individual cells together to achieve useful levels of voltage and current, and putting them in a sturdy frame complete with positive and negative terminals.

How much sunlight energy does our PV cell absorb? Unfortunately, probably not an awful lot. In 2006, for example, most solar panels only reached efficiency levels of about **(41)\_\_\_\_\_\_** to 18 percent. The most cutting-edge solar panel system that year finally muscled its way over the industry's long-standing 40 percent barrier in solar efficiency -- achieving **(42)\_\_\_\_\_\_\_** percent [source: U.S. Department of Energy].

# Energy Loss in a Solar Cell

Visible light is only part of the electromagnetic spectrum. Electromagnetic **(43)\_\_\_\_\_** is not monochromatic -- it's made up of a range of different wavelengths, and therefore energy levels.

­Light can be separated into different (**44)\_\_\_\_\_\_\_\_\_,** which we can see in the form of a rainbow. Since the light that hits our cell has photons of a wide range of energies, it turns out that some of them won't have enough energy to alter an electron-hole pair. They'll simply pass through the cell as if it were transparent. Still other photons have too much **(45)\_\_\_\_\_\_\_\_\_\_\_\_.** Only a certain amount of energy, measured in **(46)\_\_\_\_\_\_** volts (eV) and defined by our cell material (about 1.1 eV for crystalline silicon), is required to knock an electron loose. We call this the **(47)\_\_\_\_\_\_\_\_\_\_\_** of a material. If a photon has more energy than the required amount, then the extra energy is lost. (That is, unless a photon has twice the required energy, and can create more than one electron-hole pair, but this effect is not significant.) These two effects alone can account for the loss of about **(48)\_\_\_\_\_\_\_\_\_** percent of the radiation energy incident on our cell.

Why can't we choose a material with a really low band gap, so we can use more of the photons? Unfortunately, our band gap also determines the strength (voltage) of our electric field, and if it's too low, then what we make up in extra current (by absorbing more photons), we lose by having a small voltage. Remember that power is voltage times current. The optimal band gap, balancing these two effects, is around **(49)\_\_\_\_\_ eV** for a cell made from a single material.

We have other losses as well. Our electrons have to flow from one side of the cell to the other through an external circuit. We can cover the bottom with a metal, allowing for good conduction, but if we completely cover the top, then photons can't get through the opaque conductor and we lose all of our current (in some cells, transparent conductors are used on the top surface, but not in all). If we put our contacts only at the sides of our cell, then the electrons have to travel an extremely long distance to reach the contacts. Remember, silicon is a semiconductor -- it's not nearly as good as a metal for transporting current. Its internal resistance (called **(50)\_\_\_\_\_\_\_\_\_\_\_\_ resistance**) is fairly high, and high resistance means high losses. To minimize these losses, cells are typically covered by a metallic contact grid that shortens the distance that electrons have to travel while covering only a small part of the cell surface. Even so, some photons are blocked by the grid, which can't be too small or else its own resistance will be too high.